CONTRIBUTIONS TO THE MECHANISMS OF THE LIGHTNING STROKE*

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ABSTRACT

The writer's earlier paper on the mechanism of the cloud-to-ground lightning stroke was based on classical observational data. The report on the last 10 years' observations of strokes from Monte San Salvatore by Berger and Vogelsanger using improved instrumentation calls for a reassessment of the theory and makes possible a tentative extension to the intracloud stroke mechanisms. The salient new findings from Monte San Salvatore are summarized. The theory of the writer is then considered in terms of the observations. The theory in general is confirmed by these observations and certain more hypothetical conjectures are confirmed by the greater detail available in the new observations. No serious contradictions appear requiring alteration of the theory. Probably the most significant new observations deal with the nature of the positive leader strokes which had not previously been observed in detail. These, together with the very important 1964 observations of Brook and Kitagawa on intracloud strokes, furnish the basis for a tentative analysis of the mechanisms active.

1. INTRODUCTION

On the basis of recent findings on the physics of sparks, the writer (Loeb [17]) ventured to attempt to delineate the mechanism of the negative cloud-to-ground lightning stroke. While the various physical processes active are now fairly well understood, the data on the development of lightning stroke channels at hand were relatively meager. Except for the time resolved photographs of distant cloud-to-ground strokes largely due to the brilliant investigations of Schonland [28, 29] and Malan and Schonland [18] and some less well controlled investigations of McEeachron [19, 20] on the Empire State Building, the observational material on the sequence of events was meager indeed. Very recently the remarkable report of Berger and Vogelsanger [2] on lightning stroke observations on Monte San Salvatore during the years 1955 to 1965 was sent the author by Dr. Berger. The work reported was carried out by simultaneous current, still photographs, and moving film camera photographs at two speeds and in some cases from observations at two distances of strokes to the two towers on Monte San Salvatore. Other flashes in the surrounding region were also recorded. The richness of detail available from the closer views of the strokes, together with the fortunate location of the Observatory in a region much closer to the charged cell elements of the clouds, gave data on discharges from both polarities of cloud and of grounded objects. The observations, while in general confirming the validity of some of the writer's principal conclusions, permit him to correct the picture previously presented in some details. They go further in that they enable him not only to delineate the course of the cloud-to-ground stroke but in some measure that of intracloud strokes as well. In what follows the salient new facts developed by Berger's observations will be summarized. These will then be applied to the correction and extension of the writer's earlier theory.

2. NEW FACTS FROM BERGER'S OBSERVATIONS

1. The writer (Loeb [17]) had indicated that to initiate the cloud-to-ground stroke there had to be a *sudden* creation of a potential gradient between two cloud elements in excess of the order of 10 kv./cm. over an extended region containing water drops. Similarly Berger's observations clearly establish that lightning discharges moving upward from grounded conductors, such as his towers, also occur through the sudden creation of high fields at the towers in consequence of antecedent discharges in the clouds. To quote from his paper (in translation), "It looks as if the upward strokes occur only at the same time as cloud-to-cloud strokes, or connect on to cloud-to-cloud strokes."

2. The observations next revealed that strokes observed could be divided into four groups. These were:

a. Negative cloud-to-ground strokes (many)
b. Positive cloud-to-ground strokes (one only)
c. Negative ground-to-cloud strokes (many)
d. Positive ground-to-cloud strokes (many)

As might be expected, groups c and d only occur from protruding ground elements such as towers, buildings, poles, relatively isolated trees, or exposed mountain peaks. Only one case of group b was observed. Group a was of

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very frequent occurrence, and from the towers group d was also prominent.

In the past, virtually all studies came through observations from the ground of distant strokes which almost exclusively came from the base of clouds which were negatively charged. The location of the Monte San Salvatore Observatory was such that the observations were possible from regions much nearer the cloud base. Under these conditions the towers were exposed to the influence of the more diversely charged cloud elements. However, even under these conditions the group c strokes appear not to have been *directly* stimulated by positive charge elements nearest the towers. As stated above, they appear to have resulted from an intracloud stroke that suddenly lowered positive charge to the neighborhood of the towers or high ground.

No previous negative ground-to-cloud strokes had been recorded with certainty. McEachron [19, 20] had noted positive ground-to-cloud strokes but his data were not well controlled, and will not be discussed further.

3. In many cases the ground strokes originating at Berger's tower connected with oppositely charged cloud elements or their leader strokes. This was so frequently the case with the positive ground-to-cloud strokes that the records were difficult to interpret because of the early junction with negative cloud-to-ground stroke branches. In fact it is conceivable that these positive ground leaders are just exceptionally long junction leaders, to be mentioned later. This makes type d strokes exceptional type a strokes. In contrast, the negative ground-to-cloud strokes generally had their branches extending to the cloud cover. A certain number of short negative ground strokes that did not extend to effect a junction were observed.

4. As a result of the ground-to-cloud strokes, especially from the towers, there was strong evidence that in virtually all negative cloud-to-ground strokes the stepped leaders were met by positive strokes or leaders from the ground. These could generally not be photographed as in the 20-m. to 70-m. length, the currents had not increased to much above 100 a. and were thus not capable of affecting the film. Their presence could be inferred from the current traces which indicated currents of the order of 100 a. but occasionally going to 1000 a. just before the heavy return stroke of the order of 5 to 100 ka. More convincing were the moving film photographs of the negative stepped leader. The steps appeared to effect junction with the return stroke trace at some 20–70 m. above the tower and the return stroke at the juction point moved upward from above the point and downward to the tower below the point. The speed of advance was lower for the downward portion of the stroke than for the upward one. Such action is common even for positive ground-to-cloud strokes. For want of a better name it is suggested that they be termed junction leaders; Berger calls them "Fangentladung"—literally capture discharges.

As indicated, the junction point for the negative ground stepped leaders in most cases was from 1000 to 1800 m. above the tower with a short one reported at 500 m. For the positive ground leader the junctions with the downward branches of negative stepped leaders were nearer the tower.

5. Among the more important observations were details of the stepping process obtained because of the improved moving film camera design and the proximity of the strokes. Distances of the cameras to the towers were about 365 m. at the Observatory and 3.2 km. from Mt. Breganzano. This allowed about 100 m. and 1000 m. respectively at the base of the strokes to be photographed.

a. *Negative leaders,* whether from cloud-to-ground or ground-to-cloud, *were all stepped.* Step lengths were not uniform. Branching and crooked channels made measurements uncertain. The step lengths ranged from 8 to 10 m. for upward leaders and from 5 to 18 m. for downward leaders. The stepping intervals ranged from 30 to 50 μsec. There were real intervals of dark between bright step elements. According to Berger, advance ceased between steps. That is, the bright steps were linear and stopped abruptly with no sign of displacement in time. The speeds ranged from 8.5×10^6 cm./sec. to 4.4×10^7 cm./sec. for most of the negative leaders but occasional slower and faster ones were noted.

b. An important item deals with the controversial question of the diameters of the bright steps (Loeb [17]). The apparent widths of the luminous traces ranged from 1.6 m. to 2.5 m. The motion of the film during the advance of the step could have contributed to the broadening unless the step was very rapid and luminosity lasted only a very short time. Actually the luminosity persisted faintly for at least 10 μsec. as shown by the faint shadows to the right of each bright trace. If one includes corrections for halation effects such as discussed by Evans and Walker [9], it is probable that the stepped leader channels could be under a meter in diameter.

c. Another observation made by Berger on the basis of his films with negative upward leaders from the towers indicated a corona streamer discharge, "Büschelentladung," at the tips of the bright steps. This Berger took as a proof of the existence of the pilot leader.

d. Of great interest is the observation that the luminosity of the steps did not terminate with the step but persisted up the channels of previous steps in some cases from 15 to 20 step lengths towards the cloud or down to the point. That is, the luminosity persists over distances of 200 m. or extends in times to the order of a millisecond for both downward and upward stepped negative leaders. In only one of Schonland's published traces is this important phenomenon observed. These observations were from close strokes. When viewed from Mt. Breganzona at 3.2 km. only point-like luminous steps were recorded. Since intervening spaces were dark, this means that every step advance sends a new potential gradient wave back up the channel, just as the writer had postulated, for the channel is dark for 30 to 50 μsec. between.

e. In all, 46 positive strokes from the tower were observed. Of these seven had leader strokes that were photographed. Some of these showed a type of stepping differing from the negative steps. The remaining 39 strokes, which branched upward as judged from still photographs and indicated positive polarity, showed no photographed leaders or luminosity preceding the return stroke. In the two cases shown strokes came from both towers. Similar stepping was also noted in the one positive cloud-to-ground stroke. Interpretation of the details of the motion is difficult since the crooked path imposes inclinations on the luminous channels which are not related to the sense of motion of the exciting and ionizing waves of potential gradient which must be moving along the channels. The steps are most clearly seen from Mt. Breganzano as bright dots, each one of which is connected by a luminous channel to the tower. At 365-m. distance and up to 100 m. from the top of the tower the individual steps are faint, diffuse, and irregular. The lengths varied from 4 to 40 but generally ranged around 8 m. The interval between steps ranged between 40 and 115 μsec. but averaged around 80 μsec. The speeds of the leader tip advance ranged from 4×10^6 cm./sec. for four strokes to 9×10^7 cm./sec. for some 14 others. As indicated, the whole path from the step tip to the anode was luminous. The luminosity fluctuated among successive steps but generally increased as the paths lengthened to 500 m. approaching the return stroke. Each channel was brightest at the left or on the temporally leading edge and diminished in luminosity with time. In general, luminous channels were almost as wide as the dark pauses between new advances. The duration of the luminosity in the channels was of the order of 50 μsec., perhaps somewhat less than the duration of advance of the bright step, indicating possible continued current flow.

A great deal is known about the induced impulse corona and breakdown from a positive point for smaller diameter points and shorted gaps up to 1 m. (Loeb [15]). In the high field region a primary positive streamer tip is evolved with excess positive charge and a dense plasma. This advances into the gap increasing in strength in the high field region. Beyond this it advances through the action of its high space charge field by means of photoionization of the gas in advance (Dawson and Winn [8]; Dawson [6, 7]). As it advances it branches. It leaves behind a weakly conducting plasma channel up which flow the electrons created in the advance. As these electrons converge from the various branches into the high potential anode field the field causes increase of ionization near the point initiating what is called a highly conducting luminous *secondary* streamer. The primary streamer tip moves with speeds ranging from 4×10^6 cm./sec. in the lower field regions before it ceases to advance, but the speeds near the point range up to 2×10^8 cm./sec. (Dawson and Winn [8], Dawson [6, 7], Nasser [21, 22, 23], Nasser and Loeb [24], Waidmann [31]). The highly luminous positive streamer tip moves so rapidly that it is not detectable by eye under many conditions and can only be photographed as a general haze after many hundreds have been superposed. If, however, it reaches the cathode *or encounters a negative space charge* (Wagner [30], Oshige [27]), it increases its speed and luminosity. In either case it sends a very fast potential gradient wave up the channel (Loeb [16], Winn [32]). In some cases this renders the channel more luminous by increasing the carrier density. It also causes the secondary streamer to advance. In so doing it may reflect back down the channel and enhance the primary tip space charge if this has not reached the cathode, thus causing it to advance farther if it was initiated by encounter with the negative avalanche space charge. It may also reflect from the cathode. Kritzinger [13, 14] in meter-long sparks has observed as many as five such back-and-forth pulses where the primary streamer tip reached the cathode. Again, at speeds of 5×10^8 to 10^9 cm./sec., these pulses may not be visible but they will leave the channel conducting. The progress of such streamers and pulses can be studied by photomultipliers. It has also been observed by Oshige [27] that when accelerated negative charges from the cathode, or avalanches from photoelectrons, strike separate advancing streamer tip branches, the convergence of the waves of gradient at *major branch junctions near the anode* lead to *mid-gap* secondary streamers which move in both directions making the channels luminous and in crossing cause the arc. These secondary streamers have speeds in shorter gaps of the order of 10^6 cm./sec. and more.

Things cannot be vastly different when high impulse fields about the tower conductors initiate streamers. These differ in that the conductors have larger diameters and that the high potential gradients extend out much farther from the points. The nature of these streamers which constitute Berger's positive leaders is not known. They may consist of a group of partially parallel streamer tips or the conditions may create one very much more extensive large streamer tip. This advancing in the high field will continue to propagate indefinitely as Dawson and Winn [8] (p. 168) have shown.

Obviously these positive leaders appear to be able to advance some hundreds of meters in the high field in most cases (39 out of 46 observed) without leading to photographed traces though they register currents of perhaps a few hundred amperes. Once they encounter the negative space charges of the cloud or charges left by some antecedent stepped leader process from the cloud, the rapid advance begins. Potential gradient waves sweep down the channel to the tower starting the highly visible secondary. This could develop in a stepwise fashion as the space waves course back and forth from the negative cloud charges to the tower point if the charges are sustained. If one considers distances ranging from 100 to 1000 m., the stepping times are easily accounted for by the back and forth movement of space waves (Loeb [16], Winn [32]) at speeds ranging from 5×10^8 to 4×10^9 cm./sec. These speeds have actually been observed in decaying spark channels from 11 to 220 μsec. after the spark by Winn [33] and are those of such waves in Schonland's dart leaders.

This type of action with the stepwise advance of the luminous secondary upward along one or two main branches draining different negative areas would account for the few positive stepped leaders observed. It would also explain the continuous luminosity of the portion behind the tip of the secondary. It is noticed that in the case of the stepped positive leaders from the tower there was no sharp return stroke noted either on the photograph or on the current oscillogram. It would appear that in this case the positive tower streamers encountered rather extended regions of negative space charge and did not connect with very conductive negative leader tips. Such charge distributions would be expected to be rare.

Most of the positive streamer or leader systems observed advanced and branched unphotographed until one or two branch tips encountered the *tips of advancing negative stepped leader strokes*. Here the high potential gradients would establish a completed lightning stroke channel essentially the same as with junction leader strokes. It is probable at the junction of the streamer branch tips with the negative steps which invited the streamer advance that the return stroke and heavy current is preceded by a very intense and fast potential gradient wave that converts the streamer leader channel into a junction leader channel.

In the case of the one positive stepped leader advance from the cloud there was a return stroke on its arrival at the tower. This arose since it certainly effected a junction with a stepped leader from the negative ground which it invoked. There it is noted that the stepping ceased as the streamer tip reached about 0.5 msec. before the return stroke. As it did so its speed was increased and its luminosity in consequence decreased.

6. Berger's restricted observational ranges of length for the strokes in his time resolved photographs, which limited observation to about 100 and 1900 m. respectively, did not permit much resolution in the study of dart leaders associated with multiple strokes in a flash. In this respect his data are less complete than those of Schonland. He states that multiple strokes occur relatively frequently and, with rare exceptions, *only* with strokes from *negative cloud-to-ground*. This is to be expected in view of the generally accepted findings of Schonland [29], Clarence and Malan [5], Kitagawa and Brook [11], and others on the discharge of a cloud cell in successive steps following further cloud drainage by positive streamers after each stroke. This unipolar behavior follows from the sense of the funneling action of positive water drop spray corona in collecting negative charge from a larger cloud area and effectively transporting it to the narrow discharge channel. The inverse action of funneling charge from a positive cloud volume by negative streamers from the water drops is highly inefficient since liquid water surfaces do not readily yield a negative corona. Negative corona streamers do occur in air but require higher fields than do positive corona streamers and then radial branching is not prolific (Nasser [21, 22, 23], Nasser and Loeb [24], Waidmann [31]). At spark breakdown fields and above or, better, at the corresponding values of E/p (field strength to pressure ratios) if fields extend over sufficient lengths, negative streamers do progress (Loeb [17]). Unlike the positive streamers they generally progress in the direction of the necessary high guiding field and do not show the extensive branching needed for cloud drainage. Ice crystals in adequate fields could yield negative streamers but so far these have not been observed in the laboratory or on high tension powerlines.

Berger observed that in some cases the channel of the dart leader is stepped. In one sequence of four strokes from a negative cloud the initial leader was clearly stepped with 22-m.-long steps and 40 μsec. between steps. The speed was 4×10^7 cm./sec. After the rather faint return stroke a second negative leader appeared. It was finely stepped with steps perhaps 1 m. long having stepping intervals of less than 4 μsec. and a speed of the order of 10^8 cm./sec. This led to a very bright return stroke. The following two dart leaders had speeds of the order of 10^9 cm./sec. and showed no steps. These observations are in keeping with what one might expect from Winn's [33] studies when sharp potential pulses are applied to decaying spark channels. Apparently after the first stroke the ionization in the decayed first channel was not adequate to support a dart leader, or else the recovery of potential by cloud drainage was not adequate or was too slow. Hence, a *new stepped leader was required* to render the channel conducting. As there was preexisting ionization, the steps were short and speeds were high. In another case such a stepped leader to a second stroke had to forge an entirely new channel near the ground so that stepping became more conventional towards the end of the path.

3. APPLICATION OF NEW FACTS TO LOEB'S THEORY

It is now possible to reconsider the writer's mechanisms in the negative cloud-to-ground stroke, as well as those of the intracloud stroke.

1. The new data do not materially alter the concept of cloud drainage by positive hydrometeor induced streamers and the consequent funneling of charge. If anything, the new data confirm this process by adding statistical evidence both in regard to negative cloud strokes and in some observations on the sequence of strokes within the flash.

2. In the matter of stepping for negative cloud-to-ground or negative ground-to-cloud strokes there is valuable corroborative evidence.

a. The observation that negative leader strokes, whether from the cloud or from a grounded object, are all stepped indicates that this process is one inherent in the negative charge advance and is not directly connected to charge drainage pulses from the cloud. It points to the inherent weakness of the dissipative negative streamers to advance far in the absence of a strong guiding field. This is in contrast to the positive leader advance via positive streamers which leads to return strokes in most cases with no evidence of stepping. Photographed leaders and stepping there occur only under unusual circumstances. These conclusions are in excellent agreement with inferences from cloud-to-ground and intracloud strokes by Kitagawa and Brook [11] in 1960 and confirmed in 1964 [3, 26].

b. The strokes viewed from near the ground in Berger's studies generally have shorter steps ≈ 10 m. relative to those of ≈ 50 m. observed near the cloud level in longer strokes by Schonland, where the leader stroke tip fields are probably higher and more extensive. Furthermore, clearly defined steps in Schonland's obervations were seen only in the more vigorous strokes. The speeds were about those assumed in the theory and are consistent with Wagner's [30] and other streamer data (Loeb [15], Nasser [21, 22, 23], Nasser and Loeb [24], Waidmann [31]).

c. There were clearly defined dark periods between bright steps during which the relatively invisible mid-gap streamer breakdown characteristic of the pilot leader of the Wagner-type took place (Wagner [30]). The irregularity of dark intervals supports rather than negates the possible continual slow advance of the negative pilot leaders at the time that the bright step is launched as indicated by the writer (Loeb [17]).

d. The diameter of the pilot leader—bright step channel—appears more likely to lie at values less than a meter.

e. The observation by Berger that a brush discharge extends beyond the confines of the bright step merely reveals the fact that there are upward positive streamer-like irregularities in the upper end of the dark pilot leader channel. That is, the pilot leader channel is not uniformly conducting on a microscale but consists of groups of upward moving and branching channels which are revealed by the space wave of the bright step. These are prominently illuminated by the wave of potential gradient that illuminates the bright step.

f. Of greatest importance is the observation that following or accompanying, the downward motion of the bright step a wave of potential gradient sweeps back for *perhaps 200 m. or more up the channel that was dark between steps.* This must proceed at speeds of about $1–2\times10^9$ cm./sec. and re-illuminates the dark leader channel. This was, in fact, postulated by the writer (Loeb [17]). Such illumination might also in part account for the difference in step length reported in some of Schonland's observations relative to those of Berger. Such waves increase and maintain the conductivity of the channel. After the excited states radiate, the channel is again dark while the pilot leader forges ahead. As the negative streamer tips weaken and slow their advance, the current down the channel during the 30–50 μsec. of darkness builds up the potential gradient at the end of the last bright step that will help initiate the next step. To what extent the initiation of new steps is affected by the reflection of the potential gradient waves from the end of the last bright step and the motion of the upward positive streamers as affected by encountering descending electron swarms (Loeb [17]) remains to be determined.

One fact certainly emerges from Berger's observations. This is that lack of sensitivity in our only present photographic means of resolution does not permit us to learn enough about the faint but vital processes at work. Unfortunately the two-photomultiplier technique so revealing in spark growth study is at present not applicable to lightning channel study.

3. The physics of Berger's newly observed positive ground-to-cloud and the one positive cloud-to-ground strokes has been adequately discussed in the presentation of Berger's observations except for the initiation of the positive cloud-to-ground stroke which must come under the discussion of the intracloud stroke.

4. The problem of the intracloud strokes, that are by far the most frequent strokes, presents some difficulties in regard to the question of funneling of the positive charge into the future lightning stroke channel. The problem was particularly difficult as long as discussion was confined to the mechanisms involved in raindrop-laden clouds.

Generally speaking most of the positive charges in thunderstorm clouds lie in cloud elements in the upper levels of the cloud. Thus in many cases the intracloud strokes must occur between positive and negative cloud masses in which the charge resides on solid hydrometeors. There are undoubtedly in large thunderstorm cells heterogenous water-laden elements with opposite polarities. However, too little is known about such structures and one is largely constrained to consider the strokes between cloud elements where the positive charge resides on ice or snow crystals while the negative charge resides on *either ice* or *water droplets*. One added factor ameliorates the intracloud stroke problem. This is that the charged elements are in general in much closer proximity than is the case for the cloud-to-ground stroke, and they are usually in regions of much greater turbulence with higher relative speeds. In most cases the strokes all occur in hydrometeor-laden air in contrast to the clear air cloud-to-ground stroke. At the altitudes of these strokes the lower atmospheric pressure may somewhat lower the potential gradients needed.

The failure to attempt to reslove this problem at an earlier date must in a considerable measure be ascribed to the writer. He had Bandel [1] study corona from ice points to see whether one could get positive and negative corona from them. Water usually yields only positive corona since its surface disrupts into drops before surface fields adequate to give a negative corona can be achieved. To work with corona points Bandel had to resort to low temperatures. He obtained *positive* and *negative* corona from his corona points. However, at his low temperatures the conductivity of the ice was too low to yield currents of importance for breakdown processes. Thus the writer discounted the role of ice crystals in cloud drainage. It was not until F. W. Warburton (Newell et al. [25]), of the New England Power Service Company, photographed positive corona plumes from snow and ice particles on high tension powerlines at around 24 kv./cm. that exceeded those from water drops that the writer's erroneous conclusions were corrected. His measurements showed that down to $-18°$ C. the conductivity of atmospherically condensed water ice is such as to permit very extensive positive corona, especially from such pointed configurations as snow crystals. Warburton believes also to have observed negative Trichel pulse coronas from his ice points. No negative streamers have been definitely observed from ice points but it is believed that at adequately high fields they would occur.

The conclusion is that ice crystals are perhaps more proficient at yielding positive corona streamers than are the water drops as they do not shatter. They may at sufficiently high fields yield negative corona streamers. Thus in the intracloud stroke given the sudden creation of fields of the order of 20 kv./cm. and perhaps as low as 10 kv./cm. especially at lower pressures solid hydrometeor will yield charge funneling positive coronas capable of draining the negative charge and producing breakdown fields at the narrow ends of the discharge funnel facing the positive space charge clouds. They can also produce fields that lead to negative streamers in clear air. Such fields should also liberate negative streamers from ice crystals in effective amounts. The negative streamers have short ranges (about 1/3 or less than positive in low fields) and are largely field oriented in their advance (Loeb [15], Nasser [21, 22, 23], Nasser and Loeb [24], Waidmann [31]). They branch relatively little and of themselves should not act as efficient funneling or drainage agents. However, as they advance and deliver currents equal to their positive streamer counterparts they *distribute their excess negative charge radially* as rapidly repelled free electrons or negative ions about their trajectory. The region in which they are advancing in the form of a negative pilot leader is surrounded by neutral or positively charged ice particles. These ice particles are in the high field of the negative leader tip. Hence the ice crystals will generate positive streamers that will be enhanced by the electron clouds expanding radially by self-repulsion and field action. These could focus the positive streamers towards the advancing negative leader. Thus radial drainage of the positive streamer emitting ice particles stimulated by the radial electron clouds of negative leaders should be able to create a charge drainage and funneling mechanism from the positive cloud into the advancing negative stepped leader channel from the negative cloud.

The studies of Brook and Kitagawa [3], Brook et al. [4], Kitagawa [10], Kitagawa and Brook [11], and Kitagawa et al. [12] indicate that the intracloud stroke differs materially from the cloud-to-ground stroke. It appears to consist of a more or less continuously advancing unstepped positive streamer akin to the majority of positive leaders noted by Berger. When this leader meets the upward stepped negative leader at a later time it precipitates the first stroke. Thereafter, a succession of strokes associated with the so-called K changes of from 3.5 to 8 coulombs follows draining the negative and presumably the positive cloud. These are analogs of the dart leaders in the cloud-to-ground stroke. The K changes last 1–3 msec. with average currents of 1000 to 4000 a. The K change channel averages probably between 1 and 3 km. of length and the speed of the space waves of the K changes are of the order of 2×10^8 cm./sec. The continuing positive current streamer initiating the intracloud stroke has a duration of 0.1 to 0.3 sec. This would represent a speed of tip advance over some 3 km. of the order of 10^5 to 10^6 cm./sec.

These observations derived from field changes certainly place restrictions on any theory of breakdown mechanisms, since they indicate the sequence of the events. Evidentally a positive streamer channel, possibly with luminous tip, advances at a relatively slow speed from the positive charge center towards the negative charge center. The downward advance of the positive leader is unstepped, as appears to be the case in most of Berger's positive leaders. At the same time the channel must at its upper end be advancing and draining the top of the positive storage cell. At the same time as it advances into the negative storage cell it must initiate an upward advancing negative leader. When the two leader tips meet the first stroke ensues as bright space waves akin to those in the cloud-to-ground stroke. Later discharges appear as K change discharges draining other sections of both cloud elements.

These processes occur in a different environment from those of the cloud-to-ground stroke. First the initial discharge paths are shorter, meaning higher fields and they are accompanied by greater turbulence and at somewhat reduced pressures. Secondly the whole discharge materializes in air laden with hydrometeors, presumably ice crystals, that at adequate fields can generate both positive and negative streamers. Further, both negative and positive leaders will not be stepped as long as they are in hydrometeor laden air. Thus for example there is no certain evidence of stepping at the beginning of the negative leader stroke to ground until it emerges into clear air.

At this point one may only conjecture as to what occurs. Apparently in the region of the positive polar element of the dipole created by positive charges on ice above and negative charges on ice or water below, fields may reach values of the order of 20 kv./cm. or more in a restricted area. This initiates a breakdown of the neutral and positively charged hydrometeors emitting negative streamers upwards and positive streamers downwards. The dependence of negative streamers on high field gradients will tend to confine the breakdown channel to a relatively narrow region. The negative ions these create will be dispersed radially and encourage the funnelling of positive streamers from the ice crystals above them into the narrow channel. Thus as this channel advances *slowly upward*, draining the positive cloud storage system, it is conducting positive charges downward into the narrow channel. The lower end of this leader channel with high fields and confined positive charge will stimulate negative streamers from the ice crystals below. Since these concentrate in high field regions the positive streamer branches which are met by the negative charges from the lower ice crystals will be favored. In this fashion the positive leader channel will advance unstepped into the ice crystal laden cloud as a relatively narrow leader. Its speed of advance is however governed by the rate of cloud drainage at the upper ends of the channel such that continuity of current is assured. Since the positive streamer-negative ion radial expansion is a slow process compared to the positive streamers funnelling at the base of the negative cloud in the cloud-to-ground stroke advance will be slow.

Once the positive charge leader tip forges far enough towards the negative cloud element a negative upward moving streamer will advance to meet it. It is possible that as long as this advances in hydrometeor laden air it will not be stepped. If it emerges into clean air before the junction with the positive leader, it will be stepped. Junction of the two lead to the bright stroke with space waves moving at high speed upward and downward from the junction point. As these arrive at the positive and negative cloud cell ends of the channel, they will initiate a new intensified drainage of charge at both ends that result in the reported K change dart leader strokes.

In the complicated structure of unequally and turbulently moving cloud masses of different structures of positive and negative cloud elements, fields may change by previous intracloud discharges leading to electrical field changes and branching or directional changes of the stroke channels which follow.

4. CONCLUSION

This is about the best one can do in interpretation in the light of present physical knowledge. Hopefully it will help guide further study and interpretation of these strokes.

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